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FREE-FLIGHT RANGE MEASUREMENTS OF SPHERE DRAG AT LOW REYNOLDS NUMBERS AND LOW MACH NUMBERS

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NOTICES

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FOREWORD

The work reported herein was sponsored by the Sandia Corporation, Sandia Base, Albuquerque, New Mexico, under authority of Atomic Energy Commission (AEC), Order Number AL 67-255, Suborder 007.

The results of the tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The tests were conducted during the period from June 28 to August 8, 1967, under ARO Project No. VK1702, and the manuscript was submitted for publication on September 19, 1967.

This technical report has been reviewed and is approved.

Donald H. Meyer Major, USAF AF Representative, VKF Directorate of Test	Leonard T. Glaser Colonel, USAF Director of Test

ABSTRACT

The drag coefficients of spheres have been obtained from free-flight range tests of metal spheres at Reynolds numbers from 185 to 11,600 and at Mach numbers from 0.17 to 0.99. An analysis of the data indicates that the total errors in the measured drag coefficients are within ±2 percent.

CONTENTS

NOMENCLATURE

A	Reference area, $\frac{\pi}{4} D^2$
a	Speed of sound
C_D	Drag coefficient
D	Mean model diameter, $(D_{max} + D_{min})/2$

D_{max}	Maximum model diameter
D_{min}	Minimum model diameter
M	Mach number, $\bar{V}/a$
m	Model mass
p	Pressure
Re	Reynolds number, $\rho \bar{V} D/\mu$
T	Temperature
V	Velocity
$\bar{V}$	Average velocity
ΔV	Velocity drop over the model flight
x	Distance along flight trajectory
μ	Viscosity
ρ	Density

SECTION I
INTRODUCTION

Free-flight range measurements of smooth-sphere drag coefficients have been obtained for the Sandia Corporation at free-stream Reynolds numbers from 185 to 11, 600, based on sphere diameter, and at free-stream Mach numbers from 0. 17 to 0. 99. The test program was to provide accurate drag measurements for spheres in the range of Reynolds numbers and Mach numbers of the Sandia Metro Rocket Falling Sphere experiments.

SECTION II
APPARATUS

2.1 RANGE

The free-flight tests were conducted in the von Kármán Gas Dynamics Facility (VKF) Hypervelocity Pilot Range (Armament Test Cell, Hyperballistic (K)). This is a variable density range which is a 100-ft-long, 6-ft-diam, steel tube equipped with six dual-axis spark shadowgraph stations located at nominal 15-ft intervals along the range. Optical axes at each shadowgraph station are mutually orthogonal with the range centerline. Fresnel lenses serve as intensifying screens for the shadowgraphs, which are designed primarily to provide model position and attitude information. Exposure duration provided by spark light sources is 0. 1 μsec. Time of model flight between stations is provided by 10-MHz chronographs which provide timing values within ±0. 2 μsec. A digitized film reader is used to carry out numerical interpretations of the shadowgrams, and these are used to provide position-attitude-time histories of the model in flight.

A three-stage vacuum pumping system provides the desired range pressure which, for the present test, varied from 7. 1 to 266. 0 mm Hg. Four pressure measuring instruments were used to cover this pressure range: two Hass mercury manometers, a Baratron®, and an oil-filled micromanometer. The two Hass manometers were used over the pressure range from 15 to 266 mm Hg, and the Baratron was used over the pressure range from 10 to 30 mm Hg. Use of the micromanometer was restricted to the pressure interval from 7 to 15 mm Hg. Thus, by limiting the use of each instrument to its more optimum operating range and by observing the agreement between instruments when a region of overlap existed, it is believed that the pressure measurements are in error by no more than ±1 percent throughout the entire pressure range of the present test program.

Range temperatures were measured at six stations along the range. Copper-constantan thermocouples were used in making the temperature measurements, and a multipoint, strip-chart servopotentiometer provided their readout. Temperature variation along the range in no case exceeded 0.4 percent of the absolute range temperature during the present tests.

2.2 LAUNCHER

The test program required the development of a low speed, single-stage, pneumatic launcher, as shown in Fig. 1 (Appendix I). Before launch the model and its sabot were positioned in the launch tube and were separated from the high-pressure storage section (Fig. 1) by means of a thin plastic diaphragm. Launch was initiated when the diaphragm separating the sabot and the high-pressure storage section was mechanically ruptured by means of a sharp-edged plunger. The small volume between the sabot and the diaphragm was vented to the range until a very few seconds before launch, when a valve in the vent line was closed. This venting procedure was shown to be necessary to ensure that the sabot did not move down the launch tube prematurely.

In order to prevent damage to the models during launch, all of the models were sabot launched and were separated from their sabots at the completion of launch by means of a ring stripper device which stopped the sabots at the muzzle end of the launch tube. Thus, at the completion of a launch, the sabot effectively plugged the end of the launch tube and prevented the driver gas from entering the range with the model. The model velocity was obtained by adjusting the storage pressure in the high-pressure section and/or by adjusting the diameter of an orifice in the line between the high-pressure section and the sabot.

2.3 MODELS AND SABOTS

The models tested were solid 1/16-, 3/32-, 1/8-, and 3/16-in.-diam aluminum, 3/16- and 1/4-in.-diam copper, and 3/16-in.-diam steel precision ball bearings. The models were inspected before launch to determine their sphericity, the difference between the largest and smallest diameter measurable on each ball. These measurements indicated an average sphericity within 0.1 percent of nominal ball diameter, and in no case did nonsphericity exceed 0.3 percent of nominal ball diameter. Each model was also weighed before launch, and in no case did the measurement error exceed 0.5 percent.

Several of the model and sabot combinations tested are shown in Fig. 2. The sabots were of single-piece construction and were made of either Lexan® or Dylite®, the latter being a very lightweight foam material. In order to minimize sabot weight for a given sphere size, two different launch tube diameters were used in the present tests, a 1/2-in. bore-diam launcher for the larger spheres and a 3/16-in. bore-diam launcher for the smaller spheres. Also, the use of Dylite sabots with the lighter spheres was a further aid in minimizing sabot weight.

SECTION III
DATA REDUCTION PROCEDURE

Model velocity, as a function of downrange distance traveled, was computed from the measured model position-time history for each shot. The position of the model with respect to the range axis system was obtained from the shadowgrams of the model in free flight by means of a data reduction program written for a computer. It has been demonstrated that the measurement errors associated with velocities evaluated over the 15-ft intervals of Range K are within ±0.02 percent for the range of velocities of this test program..

The drag coefficient, C_D, was obtained from the relation

$$C_D = -\left(\frac{2m}{\rho A \bar{V}}\right) \frac{dV}{dx} \tag{1}$$

where dV/dx is the mean slope of the curve of model velocity as a function of distance traveled, and $\bar{V}$ is the mean model velocity during the observed portion of the flight trajectory. The term dV/dx is obtained by fitting a linear equation to the measured velocity-distance data by means of the least-squares procedure. Equation (1) is based on the assumption that C_D is constant during the flight. Consideration of the variations of C_D with Reynolds number and Mach number for the present test conditions indicates that the restriction of a constant C_D in Eq. (1) is adequately satisfied when the total velocity drop during the flight is limited to about 6.0 percent of the initial velocity.

It is apparent from Eq. (1) that the accuracy in measuring C_D is very dependent on the capability of measuring dV/dx. Further, it is apparent, for a given measuring error in velocity, that the accuracy in measuring dV/dx is improved as the velocity drop over the range interval is increased. However, this velocity drop must be limited by the maximum velocity drop restriction identified above. Equation (1) also indicates that dV/dx will vary appreciably for a sphere of a

given size and material when the range pressure is adjusted to provide large changes in Reynolds number. However, careful selection of the model sizes and materials used in the present tests permitted the measurement of drag coefficients throughout the test matrix with a near optimum velocity drop from, in general, about 1 to 5 percent of the initial velocity.

SECTION IV
RESULTS AND DISCUSSION

The results of the present test program to provide drag measurements for spheres at free-stream Reynolds numbers from 185 to 11, 600 at Mach numbers from 0.17 to 0.99 are presented in Table I (Appendix II), and the majority of the measured drag coefficients are also plotted in Fig. 3 as a function of free-stream Reynolds number. Sufficient data are shown in Fig. 3 to define the drag coefficient variation with Reynolds number at the nominal Mach numbers of 0.20, 0.33, 0.46, and 0.60 as requested by the Sandia Corporation. Figure 4 presents, as a function of free-stream Mach number, the drag data obtained within the Reynolds number interval $9,400 \leq Re \leq 11,600$. Within this range of Reynolds numbers the sphere drag coefficient is primarily a function of Mach number. Similar curves for any discrete Reynolds number between 200 and 10^4 can be drawn by using the faired curves in Fig. 3.

An appraisal of the possible errors associated with the experimental measurements and an examination of the consistency of the final data indicate that the total errors in the measured drag coefficients are within ±2 percent.

SECTION V
CONCLUDING REMARKS

Free-flight range measurements of sphere drag coefficients have been obtained at Reynolds numbers from 185 to 11, 600 and at Mach numbers from 0.17 to 0.99. An evaluation of the possible experimental errors and an examination of the consistency of the final data indicate that the total errors in the measured drag coefficients are within ±2 percent.

APPENDIXES

I. ILLUSTRATIONS
II. TABLE

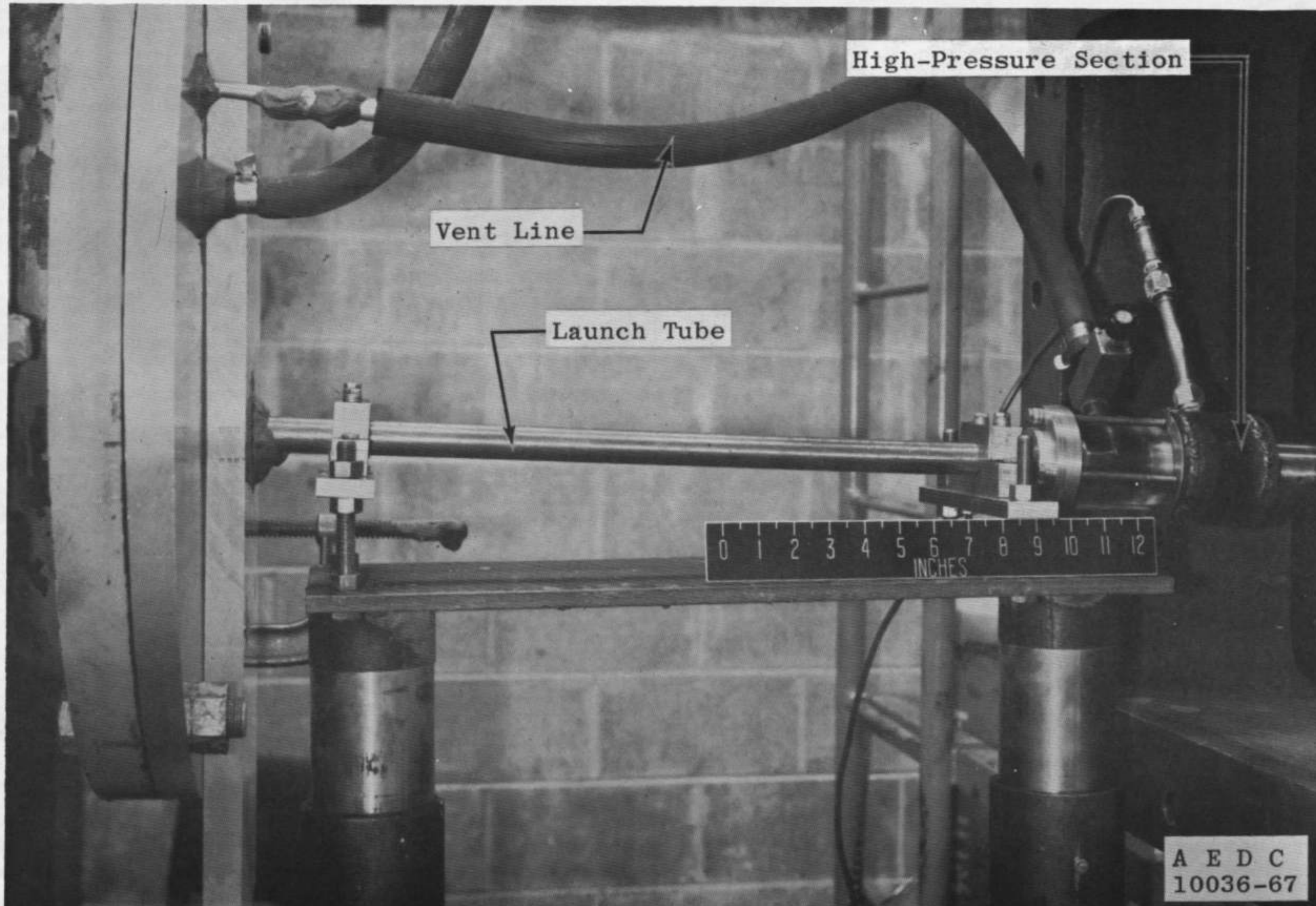

Fig. 1 Low Speed Launcher

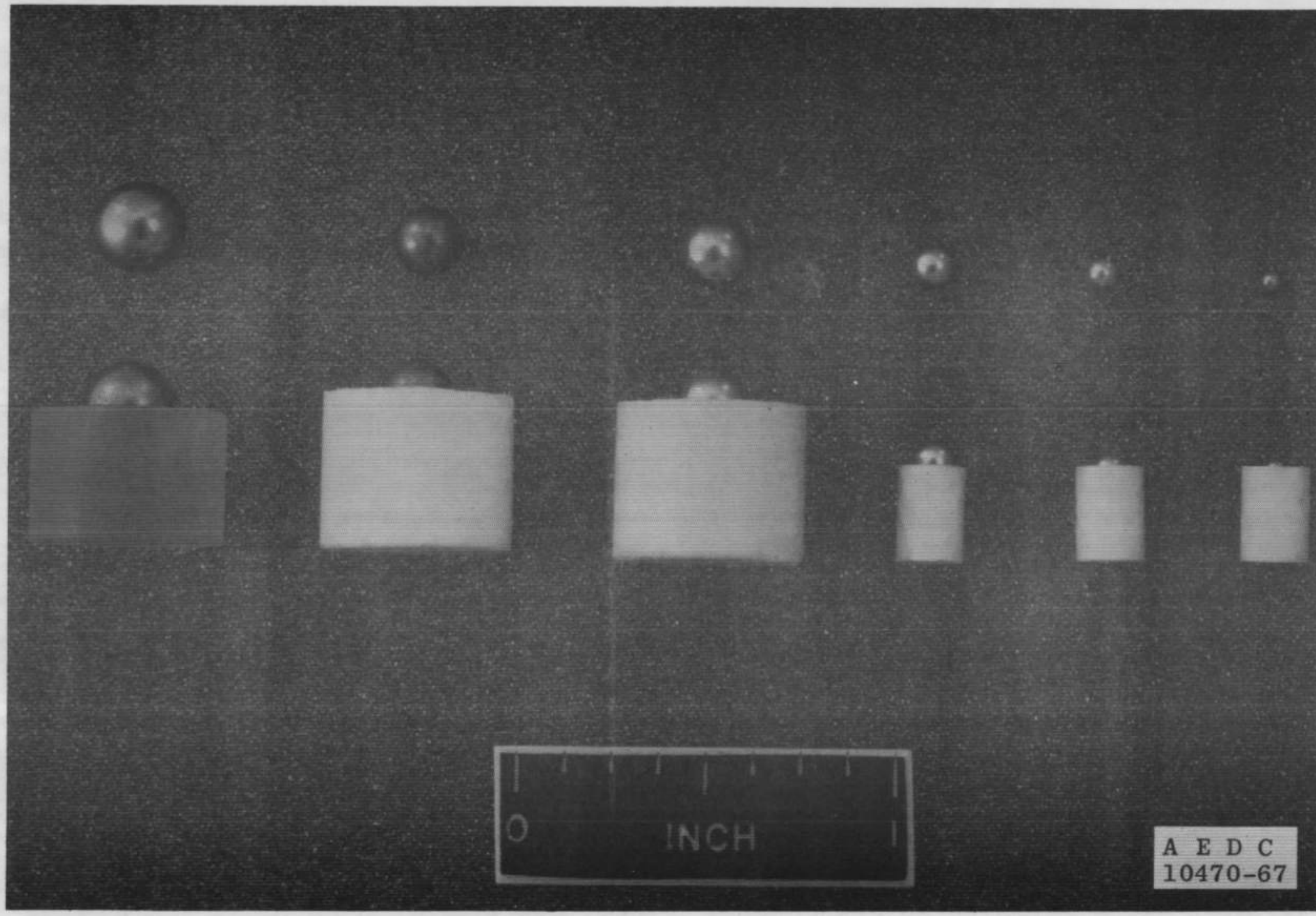

Fig. 2 Models and Sabots

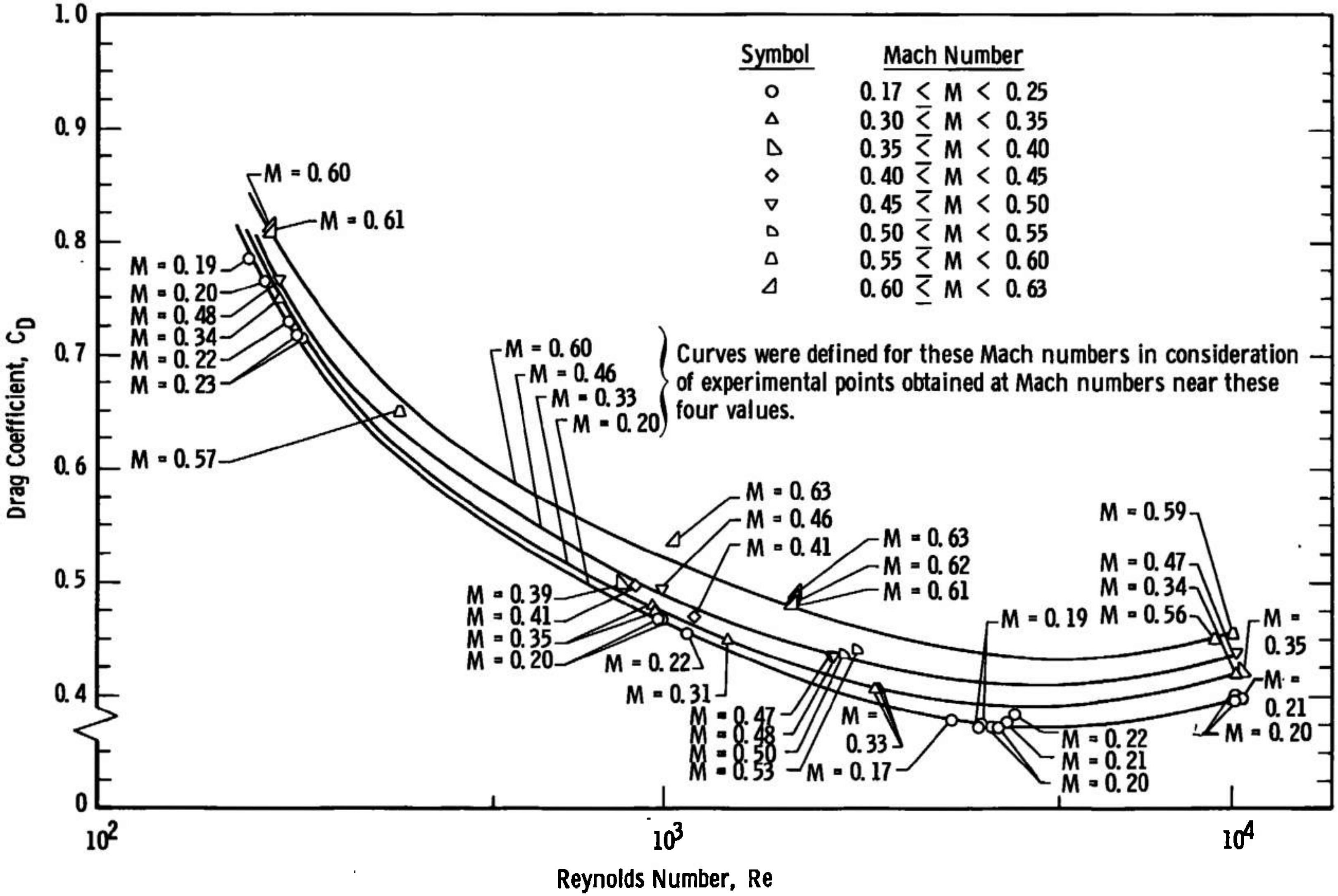

Fig. 3 Variation of Sphere Drag Coefficient with Reynolds Number

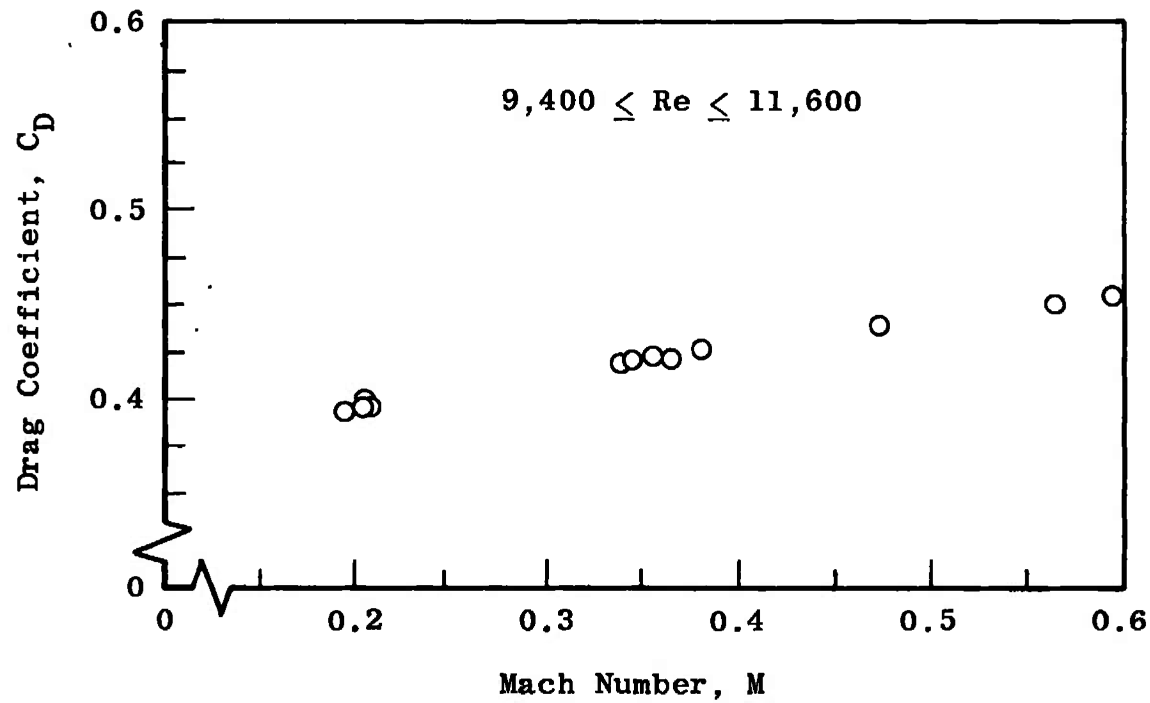

Fig. 4 Variation of Sphere Drag Coefficient with Mach Number

TABLE I
EXPERIMENTAL DATA

Shot	M	Re	C_D	p, mm Hg	T, °F	ΔV, ft/sec	Model Description		
							Mass, gm	D_{max}, in.	D_{min}, in.
1	0.406	1,130	0.469	29.4	70	15.3	0.0475	0.1250*	
2	0.564	9,480	0.450	118.3	71	20.2	0.4325	0.1877	
3	0.594	10,100	0.453	119.4	70	21.6	0.4323	0.1875	
4	0.473	10,200	0.439	153.4	74	18.4	0.4943	0.18616	0.18600
5	0.346	10,500	0.420	214.8	68	9.0	0.4920	0.18598	0.18580
6	0.365	11,100	0.421	215.3	69	14.3	0.4935	0.18602	0.18590
7	0.354	10,800	0.423	215.6	69	16.3	0.4954	0.18638	0.18605
8	0.382	11,600	0.426	215.0	68	20.2	0.4967	0.1861	
9	0.338	10,200	0.418	215.0	72	17.5	0.4952	0.1863	
10	0.343	10,500	0.421	214.8	71	20.8	0.4322	0.18752	0.18751
11	0.204	10,200	0.396	265.4	72	4.6	1.1924	0.24990	0.24980
12	0.208	10,400	0.396	266.0	71	4.7	1.1918	0.24983	0.24978
13	0.196	9,870	0.394	266.4	70	8.9	1.1926	0.2498	
14	0.204	10,300	0.401	266.0	70	9.4	1.1920	0.2497	
15	0.204	3,920	0.372	135.8	71	3.4	0.4326	0.18754	0.18753
16	0.210	4,070	0.377	137.0	72	3.6	0.4320	0.18754	0.18753
17	0.218	4,190	0.383	137.2	72	6.6	0.4946	0.1861	
18	0.210	4,050	0.378	137.6	73	6.3	0.4952	0.1860	
19	0.196	3,820	0.372	137.7	73	5.0	0.4322	0.18753	0.18752
20	0.189	3,620	0.372	136.0	70	1.4	0.4960	0.18622	0.18593
21	0.168	3,250	0.379	136.2	71	4.4	0.4327	0.18754	0.18752
22	0.190	3,680	0.376	136.2	71	4.9	0.4325	0.18754	0.18752
23	0.222	1,120	0.454	53.2	72	11.0	0.4730	0.12544	0.12538
24	0.195	986	0.468	53.5	73	11.7	0.4730	0.1253	
25	0.226	226	0.718	14.17	72	6.3	0.01970	0.09353	0.09338
26	0.231	231	0.715	14.18	72	8.6	0.01967	0.09350	0.09338
27	0.867	1,430	0.646	23.55	76	48.3	0.01970	0.0936	
28	0.712	1,170	0.557	23.37	73	21.1	0.01980	0.09372	0.09360
29	0.896	1,470	0.685	23.31	74	26.0	0.01968	0.09355	0.09346
30	0.608	1,700	0.480	29.65	74	23.6	0.0473	0.12538	0.12530
31	0.347	964	0.475	29.54	75	8.3	0.0473	0.12540	0.12534
32	0.346	957	0.479	29.31	73	9.9	0.0476	0.12541	0.12536
33	0.620	1,720	0.486	29.31	73	18.0	0.0474	0.12539	0.12530
34	0.630	1,740	0.491	29.36	73	21.6	0.0476	0.12540	0.12534
35	0.630	1,050	0.536	23.52	73	25.2	0.01990	0.09386	0.09368
36	0.739	1,220	0.563	23.44	73	35.8	0.01959	0.09353	0.09334
37	0.730	1,210	0.560	23.46	73	17.5	0.01968	0.09359	0.09344
38	0.892	1,470	0.672	23.46	73	38.1	0.01983	0.09370	0.09340
39	0.790	1,310	0.590	23.54	72	29.8	0.01984	0.09372	0.09364
40	0.791	1,310	0.584	23.42	73	34.6	0.01976	0.09367	0.09352
41	0.978	919	0.940	13.32	73	11.2	0.01975	0.09369	0.09359
42	0.898	848	0.764	13.37	73	29.3	0.01986	0.09388	0.09382
43	0.529	2,210	0.440	44.3	74	24.6	0.0474	0.12540	0.12532
44	0.312	1,310	0.448	44.2	71	12.7	0.0474	0.12541	0.12538
45	0.480	2,020	0.436	44.3	71	19.0	0.0474	0.12538	0.12529
46	0.474	2,000	0.437	44.4	71	25.1	0.0475	0.12544	0.12540
47	0.502	2,100	0.437	44.4	72	26.4	0.0476	0.12540	0.12533
48	0.473	1,980	0.436	44.4	72	25.0	0.0473	0.12540	0.12536
49	0.388	842	0.499	30.7	72	21.8	0.01962	0.09355	0.09333
50	0.412	893	0.498	30.8	72	20.2	0.01962	0.09344	0.09332
51	0.458	993	0.495	30.8	72	22.3	0.01970	0.09358	0.09344
52	0.484	210	0.768	9.236	73	11.7	0.00584	0.06240	0.06235
53	0.989	921	0.969	13.188	72	46.1	0.01985	0.09380	0.09369
54	0.948	892	0.880	13.337	73	30.4	0.01983	0.09371	0.09368
55	0.612	203	0.809	7.039	73	9.5	0.00586	0.06250	0.06245
56	0.602	203	0.814	7.144	72	9.6	0.00586	0.06246	0.06240
57	0.568	343	0.650	8.567	72	8.6	0.01980	0.09366	0.09358
58	0.345	210	0.750	12.915	71	18.3	0.00586	0.06249	0.06239
59	0.329	2,370	0.406	51.1	73	9.3	0.1590	0.18772	0.18760
60	0.331	2,390	0.406	51.2	73	12.5	0.1598	0.18799	0.18790
61	0.332	2,400	0.405	51.2	73	12.5	0.1597	0.18807	0.18793
62	0.187	185	0.787	10.589	74	4.4	0.0460	0.12434	0.12426
63	0.216	218	0.730	10.774	74	1.2	0.0460	0.12426	0.12422
64	0.197	195	0.767	10.615	74	2.2	0.0459	0.12429	0.12423
65	0.202	999	0.466	53.1	75	13.8	0.0460	0.12440	0.12421

*When a diameter value appears in the D_{max} column only, no sphericity measurements were made, hence the value in this column represents the diameter measurement used.

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13. ABSTRACT

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